From Virtual to Actual Mobility: assessing the benefits of active locomotion through an immersive virtual environment using a motorized wheelchair

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ABSTRACT

As we move around, in a real or virtual environment, the process of keeping track of where we are, in relation to the portions of the environment that are out of view, is referred to as *spatial updating*. Studies have shown that in the real world, when we use real walking to get around, this process is both effortless and automatic, but that in virtual environments, when purely virtual methods of locomotion are used, the accuracy and ease of spatial updating is significantly diminished. In this paper, we present the results of an experiment intended to assess the impact, on spatial updating performance, of enabling people to physically move about in an immersive virtual environment using a motorized wheelchair. This study is motivated by an interest in probing the potential of *re-directed driving* as an alternative method for enabling people to effectively explore a relatively larger virtual space while physically moving about in a smaller actual space.

A total of 24 participants in our within-subjects experiment traveled through a 24′ wide circularly symmetric virtual room, searching the contents of 16 randomly positioned and oriented boxes to locate 8 hidden targets, using each of the following four locomotion methods: real walking (R), virtual translation with real rotation by standing and using a body-worn joystick (S), real driving in a motorized wheelchair (W), and virtual translation with real rotation by sitting in a swivel chair and using a joystick mounted on one of its arms (J). We computed four measures of search efficiency: total distance traveled, total number of targets revisited, proportion of perfect trials, and total search time.

Overall, we found that performance was significantly better with real walking than with either of the virtual travel methods, consistent with most previous findings, and that performance with the wheelchair was intermediate. These results suggest some advantage in enabling actual, as opposed to purely virtual, translational movement in a locomotion interface, and lend support to the potential viability of a re-directed driving implementation.

KEYWORDS: virtual environments, spatial cognition, locomotion methods, re-directed driving.

INDEX TERMS: I.3.6 [Methodology & Techniques]: Interaction techniques.

1 INTRODUCTION

Previous studies have repeatedly shown that people are able to achieve a deeper sense of presence and a more robust spatial understanding of an immersive virtual environment when they are enabled to explore it using real walking, rather than using purely virtual travel in which a joystick is manipulated to update the presented view [e.g. 14, 9, 3]. A significant limitation of real walking, however, is that it cannot support the direct free exploration of a virtual space that is larger than the physically available tracked area. Re-directed walking [5] was proposed as a solution to this problem that seeks to leverage the aspects of real walking that support enhanced spatial cognition while at the same time evoking automatic spatial updating based on the visual feedback that is provided by the display rather than the physical feedback that is indicated by the movement of the body. Unfortunately, sensitivity to redirection while walking is such that the seamless illusion of unbounded free exploration requires a prohibitively large amount of space [11], and practical implementations require the use of overt interventions such as distractors [4]. Re-directed *driving* [2] was recently suggested a complementary approach in which there may be greater potential to surreptitiously dissociate the visual and physical feedback streams. However, as re-direction is trivial to achieve when people aren't physically moving at all, the practical merits of pursuing a re-directed driving approach also depend on the extent to which presence, engagement, and spatial awareness can be enhanced by allowing people to actually move through a virtual environment using a motorized wheelchair versus merely traveling virtually using a joystick.

To this end, we seek in this paper to comparatively assess the extent to which people are able to maintain spatial awareness, through automatic spatial updating, when they are allowed to explore an immersive virtual environment by actually driving through it using a motorized wheelchair rather than using a joystick to virtually move, with natural walking as a control.

2 RELATED WORK

Many previous studies have investigated the effect of locomotion method on the ability to acquire survey knowledge and on the accuracy/efficiency of spatial updating in immersive virtual environments [e.g. 13, 12, 7]. Most of these studies compared performance using a walking interface to performance using a joystick, and nearly all found significant advantages in real walking over the use of virtual alternatives.

In the domain of driving, simulators that include motion have been found to enhance the realism of the driving experience and to promote behaviour in the simulator that is more alike to behaviour in the real world, despite shortcomings in the realism of the motion cues provided [10]. Direct evidence of an important role for vestibular cues in the process of spatial updating is, however, scant. In a study that involved only rotation, and a virtual environment that consisted of a richly detailed and realistically rendered scene, Riecke *et al.* [6] found that visual information alone was sufficient to enable people to successfully re-orient themselves, and that performance was not significantly enhanced when a motion platform was used to provide vestibular cues as well. Waller *et al.* [15] found that people who received inertial cues to motion from riding in a car showed no advantage in learning the spatial layout of the traversed environment over people who were provided with the visual component of the stimulus only. In both of these studies, however, the participant was passively exposed to both the visual and motion stimuli, and did not actively control the process.

Researchers at York University implemented a mobile virtual reality system combining head-mounted-display-presented visuals with real motion using a three-wheeled bicycle [1]. They found that participants significantly overestimated travel distance in the virtual world when they were actually moving, relative to when they only pedaled but did not move, or when only visual cues to motion were available. However they did not assess the impact of the locomotion method on general spatial awareness.

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Our present investigations are modeled after a series of experiments conducted by Ruddle and Lessels [9], and recently extended by Riecke *et al*. [7], that sought deeper insight into the extent to which spatial updating performance depends on body-based cues from physical movements, focusing in particular on self-rotation. Ruddle and Lessels compared spatial updating performance across three locomotion conditions: real walking, virtual translation in combination with real body rotations, and purely virtual movement. They found significantly better results with walking, and no significant differences between either of the other two methods. However when Riecke *et al*. repeated the same comparison using more robust experimental methods, they found that participants performed significantly better when the locomotion interface allowed real body rotations than the rotational component of motion was purely virtual.

3 Our Experiment

Our experiment seeks to extend these investigations by focusing on the impact of incorporating real *translational* movement into the locomotion interface. Specifically, we compare spatial updating performance using real walking, which allows real physical translation in combination with real physical rotation, to performance using locomotion methods in which the translational (but not rotational) component of the movement is controlled by a joystick. We do not additionally consider the case of purely virtual motion as that comparison has already been made by Riecke *et al*. [7], with benefits found for the use of real rotations.

3.1 Task

Following the methodology of Riecke *et al*. [7], we used a head mounted display system to immerse participants in a realistically rendered virtual environment that was devoid of notable landmarks (figure 1), and asked them to search for 8 targets randomly hidden within 16 possible locations.

3.2 Apparatus

The virtual environment was displayed using an nVisor SX, which presents two 1280x1024 resolution images over a manufacturer-specified 60° diagonal field of view with 100% stereo overlap. The HMD was connected by a 15′ cord to a video control unit mounted on a small wheeled cart, and the VCU was connected to a desktop computer by another set of cables spanning an additional 16′. Head and hand tracking was done using a HiBall 3100, which enabled robust, high fidelity, low latency tracking with six degrees of freedom at two discrete points via sensors that were attached to the head mounted display and to a hand-held wand. The virtual environment was rendered at interactive speeds on a custom built PC with a dual-core 2.83GHz Intel Xeon processor and nVidia Quadro FX 5800 card. A composite, looping audio track played ambient, non-spatialized sounds of a running river and tropical birds through the headphones built in to the HMD. This was done to obscure any external auditory cues that might help the participant to orient themselves in the lab space. The wheelchair we used is a Hoveround MVP5. It has a 22.7 inch turning radius (pivoting about the left or right wheel), and a maximum speed of 5 miles/hour, which we restricted to 2 mph for safety reasons using a button press interface attached to the arm.

We modeled the virtual environment in SketchUp and rendered it using OpenGL and G3D. To discourage participants from colliding with the walls of our lab space while exploring the virtual environment, while at the same ensuring the absence of landmark cues that they could use to reorient themselves in the virtual world, we delimited the boundary of the navigable area using a 24′ wide x 10′ tall circularly symmetric virtual room, repetitiously textured with a photograph of a door in our lab. With this design, we sought to evoke a sense of realism and familiarity that we hoped could promote ‘presence’ and encourage people to behave naturally.

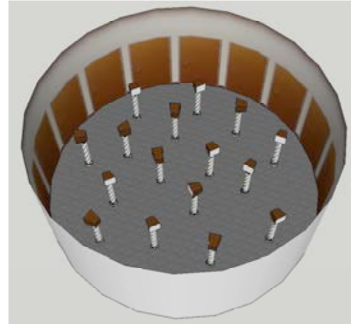

Figure 1. A birds-eye view of our virtual room model.

The room model was populated with 16 circularly symmetric pillars, which were laid out in a random pattern that was uniquely and independently determined at the start of each trial. To ensure adequate space for maneuvering, a minimum 1m separation distance was enforced between pillars and a minimum 0.5m buffer was enforced beside the wall. Atop each pillar we placed a randomly-oriented, asymmetrically shaped box that had five brown sides and one white side, which was larger than the others. Participants controlled a virtual hand model with a wand that they carried in their left hand. When the virtual hand intersected the white side of the box, the color of that side of the box would change to either red or blue, and then revert to white when the hand was removed. The heights of the columns were reduced by a constant fixed amount when participants explored the virtual world while sitting, in order to maintain approximately the same relationship between eye height, arm height, and box height across all of the locomotion conditions.

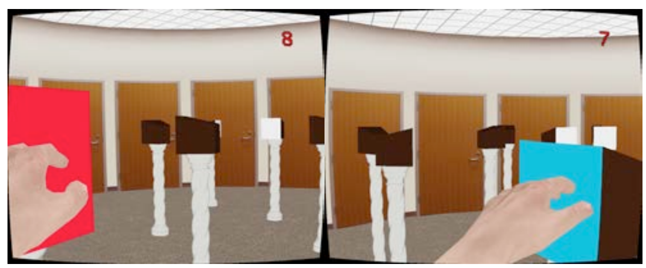

Figure 2. The virtual environment as seen in our experiment. Left: one of the sitting conditions; Right: one of the standing conditions. Note the similarity of the visual experience in each case.

3.3 Locomotion Methods

Each participant performed the search using four different locomotion methods (figure 4). We took care to characterize them using neutral terms in order to avoid inadvertently evoking any subconscious bias towards or against any particular technique:

R – Participants moved through the virtual environment by freely walking in the lab space.

S – Participants stood on a 1″ high platform (to dissuade them from inadvertently walking) and wore a rate-controlled joystick (Logitech Attack 3) on a board that was supported by straps across their back. They used the joystick with their right hand to control their forward and backward translational motion in the virtual environment and physically rotated their body to turn.

W - Participants moved through the virtual environment by driving around in the real environment using a motorized wheelchair. They controlled the rotational and translational motion of the wheelchair via the built-in joystick on its right arm.

J - Participants sat in a swivel chair that had a Logitech Attack 3 joystick mounted on its right arm. They used the joystick to translate in the virtual world, and turned by rotating the chair.

3.4 Participants

Twenty four members of the Minneapolis community participated in the study and each was compensated with a $10 gift certificate. Half were female (ages 19-57, μ= 25.7), and the other half were male (ages 18-58, μ = 25.5). All except one were right handed.

Figure 3. Photographs showing the different locomotion methods: real walking (R), joystick translation while standing (S), motorized wheelchair (W), and joystick translation while sitting (J).

3.5 Procedure

Each participant experienced each of the four locomotion conditions in a different order, so that all possible permutations of ordering were tested exactly once. For consistency, we used written instructions to explain the experimental procedure. To avoid inadvertently evoking any implicit bias towards or against any particular method, we made customized instruction sheets for each participant, introducing the different locomotion methods in the order in which that person would be experiencing them.

Each participant completed three trials per condition, the first of which was considered as training and its results ignored. Participants completed cybersickness questionnaires at the start of the experiment and after the last trial with each method. The act of filling out this survey enforced a natural break between the conditions, during which participants were required to take off the HMD and encouraged to move about the room and enjoy some snacks. The entire experiment took about one hour per person.

At the start of each trial, participants began in the center of the room, facing north. Their task was to search through all of the boxes, touching the white side of each with their virtual hand, until they had found all eight red boxes. A number in the upper right corner of the display indicated how many targets remained to be found, rendered in the stereo view at a comfortable distance away. After any box had been touched once, and the hand removed by at least 1m, it would subsequently appear blue if touched again. This forced participants to keep track of which boxes they had already visited in order to find all of the red targets. The random orientation of the boxes forced participants to frequently change the direction in which they were facing. Participants were instructed to find all of the red boxes as quickly as possible without revisiting any previously searched locations. Each trial ended either in success, after the participant had found all 8 red boxes, or in failure, as defined by Riecke *et al*. [7], after eight consecutive revisits. After the final trial, each participant was given a custom survey, listing each method in the order it had been experienced, and asking them to indicate, on a scale from 1 to 7, how much they had enjoyed using each one.

4 Results

We computed the following three performance metrics for each trial: total number of targets revisited, total distance traveled, and total time spent in the search, then used MacAnova to compute the expected mean squares for the terms in the ANOVA for the model *performance metric = subject*locomotion_method*, with subject considered as a random effect and method as a fixed effect.

Figure 4 shows an ordered histogram plot of the total number of revisits for each trial, over all participants, for each locomotion method. The trials are sorted separately for each method, from least to most revisits. The numbers of revisits per trial are shown by small colored dots, joined by thin lines to clarify the progression. The thick lines show a 6^{th} degree least squares polynomial fit to the data in each case. We found that this fit provided the best balance between staying close to all the data points and avoiding negative values and extreme oscillation.

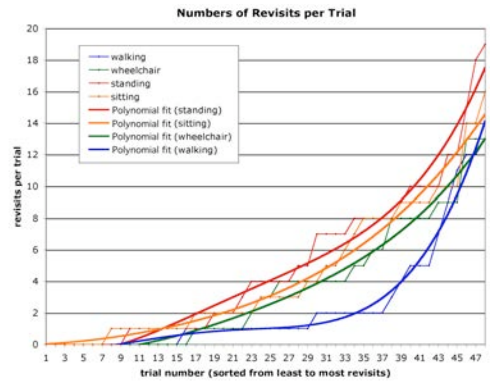

Figure 4. An ordered histogram plot of the number of revisits per trial. Thick lines show the least squares polynomial fit to the data.

Participants had the greatest number of perfect trials (16 out of 48, or 33.3%) when using the wheelchair, closely followed by walking (15 out of 48, or 31.3%). The number of perfect trials was considerably smaller in the sitting and standing joystick locomotion conditions (14.6% and 18.8%, respectively). Overall, the total number of revisits was least in the walking condition, followed by the wheelchair condition, and then the two joystick conditions. However, the ANOVA showed only a marginally significant main effect of locomotion method $\{F(3, 96) = 2.49, p = 0.068\}$, and pairwise comparisons using Tukey's Honestly Significant Difference test were not significant at $\alpha = 0.05$.

Figure 5 shows the total distance traveled during the search task, averaged over all participants for each locomotion condition. The ANOVA in this case showed a significant main effect of locomotion method $\{F(3, 96) = 9.47, p < 0.001\}$, and pairwise comparisons using Tukey's HSD test found that traversed distance was significantly shorter (at $\alpha= 0.05$) with real walking than with

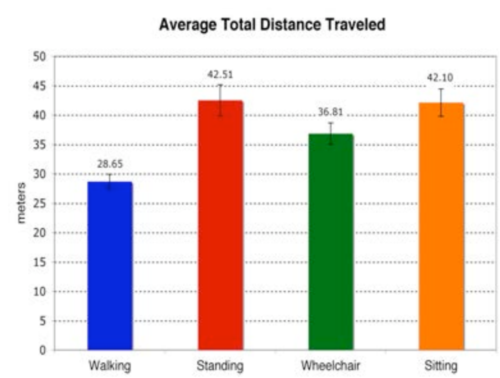

Figure 5. A plot of the average total distance traveled during the search task, over all participants in each locomotion condition. Error bars show the 95% confidence intervals around each mean.

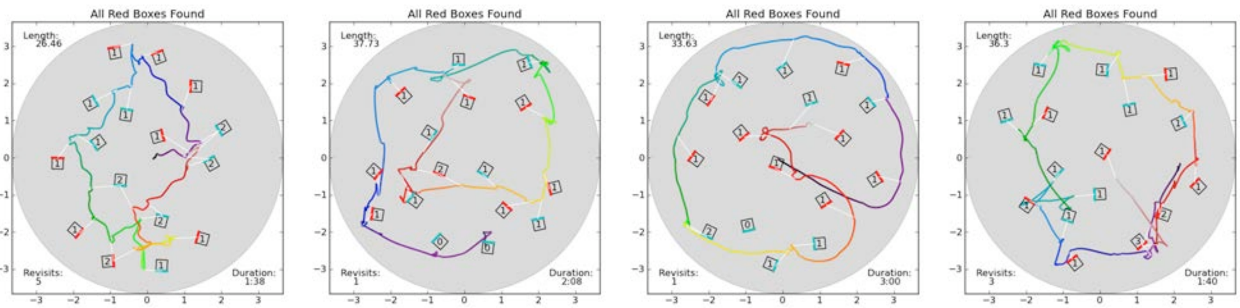

Figure 6. Representative plots showing the paths of median length, among all participants, by locomotion method. From left to right: real walking (R), joystick translation while standing (S), motorized wheelchair (W), joystick translation while sitting (J). The color coding along the path indicates the direction of travel, proceeding in reverse rainbow order (black, purple, blue, green, yellow, red, white).

any of the other methods, and marginally significantly shorter (at $\alpha = 0.055$) with the wheelchair than either of the joystick methods.

We also found a significant main effect of locomotion method on search time $\{F(3, 96) = 54.0, p < 0.001\}$, with average time being significantly faster with real walking (1.45 minutes/trial) than with the other methods, despite similar average speed in the walking and joystick conditions (0.35, 0.38 and 0.34 m/s). Both average search time (3.13 min/trial) and average search speed (0.20 m/s) were significantly slower with the wheelchair, due to the artificially imposed maximum travel rate with that device. We did, however, find a significant positive correlation between the total number of revisits, the total distance traveled, and the total search time, across all locomotion methods.

Figure 6 shows representative summary images for the trials of median path length for each method, indicating the locations, orientations, and initial colors of each box, along with the participant's path, color-coded in a reverse rainbow ordering. The white lines from the path to each visited box show where the participant was each time a box was touched. The number inside each box indicates the number of times it was searched. These images reveal characteristic features of the paths traversed using the different locomotion methods. In particular, we observe that the paths in the joystick locomotion conditions are characterized by successive segments of straight line motion, while the walking and wheelchair paths are more fluid. Whitton *et al*. [13] also noted that joystick motion does not correlate well with real walking.

Cybersickness was generally low with all of the tested methods. The average SSQ score was 12.3 and we did not find any significant differences between conditions. Finally, in the post-test survey, participants overwhelmingly rated real walking as their preferred method of locomotion.

5 Discussion

Overall, participants performed best when walking. However, performance was also better, by some measures, with the wheelchair than with the joystick. This suggests that the experience of physical motion may facilitate the process of spatial updating, enabling people to more effortlessly keep track of where they have been when exploring a virtual environment. Real driving not only provides vestibular cues to motion, but also the cognitive assurance of actual displacement. The significance of the latter is highlighted by the recent finding that the cognitive *illusion* of rotation is sufficient to facilitate automatic spatial updating even in the absence of any actual self motion [8]. Our results suggest that there may be some merit in exploring the potential of using redirected driving in a motorized wheelchair as an alternative to purely virtual locomotion for exploring virtual environments that are larger than the available tracked area.

Acknowledgments

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